

# Observations of millisecond X-ray pulsars

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**Abstract.** I present an observational review of the five accretion-driven millisecond X-ray pulsars currently known, focusing on the results obtained with the *Rossi X-ray Timing Explorer (RXTE)* satellite. A prominent place in this review is given to the first such system discovered, SAX J1808.4–3658. Currently four outbursts have been detected from this source, three of which have been studied using *RXTE*. This makes this source the best studied example of all accretion-driven millisecond pulsars. Its October 2002 outburst is of particular interest because of the discovery of kilohertz quasi-periodic oscillations and burst oscillations during its thermonuclear X-ray bursts. The other four accreting millisecond pulsars were discovered within the last two years and only limited results have been published so far. A more extended review can be found at <http://zon.wins.uva.nl/~rudy/admxp/>

## INTRODUCTION

Ordinary pulsars are highly-magnetized ( $B \sim 10^{12}$  G), rapidly rotating ( $P \sim 10$  ms) neutron stars which spin down on timescales of 10 to 100 million years due to magnetic dipole radiation. By contrast, millisecond ( $P < 10$  ms) radio pulsars have ages of billions of years and weak ( $B \sim 10^{8-9}$  G) surface magnetic fields. Since many of these millisecond radio pulsars are in binary systems, it has long been suspected (see, e.g., [1] for an extended review) that the neutron stars were spun up by mass transfer from a stellar companion in a low-mass X-ray binary (LMXB). If this scenario is correct, LMXBs should harbor a fast spinning neutron star which might be visible as an accretion-driven millisecond X-ray pulsar. However, before the launch of the *Rossi X-ray Timing Explorer (RXTE)*, all searches for coherent millisecond X-ray pulsations in LMXBs failed to yield a detection [51, and references therein]. Only after *RXTE* was launched did we obtain conclusive evidence that at least some LMXBs indeed harbor weakly magnetic neutron stars with millisecond spin periods. In April 1998 the first accreting millisecond X-ray pulsar was discovered [58] followed by the discovery of four additional systems during the last two years [26, 9, 28, 29].

## SAX J1808.4–3658

### The September 1996 outburst

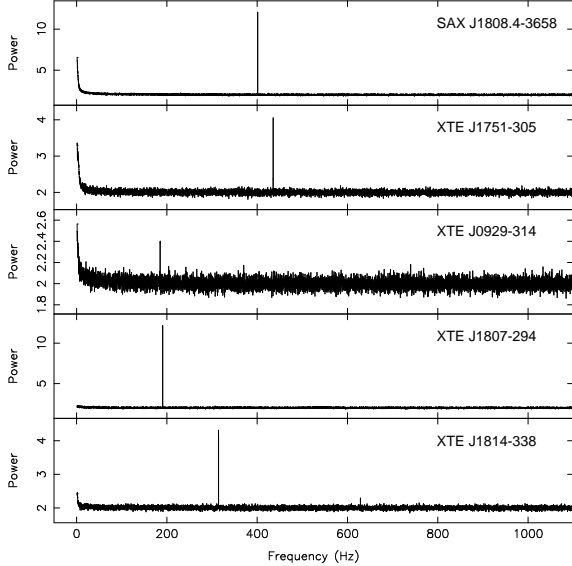
In September 1996, a previously unknown X-ray transient (designated SAX J1808.4–3658) was detected with

the Wide Field Cameras aboard the *BeppoSAX* satellite [16]. Three thermonuclear X-ray bursts were detected, demonstrating that the system harbors a neutron star. Using those type-I X-ray bursts the distance toward the source was estimated to be 2.5 kpc [16, 17], resulting in a maximum outburst luminosity of  $\sim 10^{36}$  ergs s $^{-1}$ . The outburst lasted for about three weeks, after which the source was presumed to have returned to quiescence. However, recently it was found [41] that the source could still be detected on October 29, 1996, (using data obtained with the proportional counter array [PCA] aboard *RXTE* during slew maneuvers of the satellite) with a luminosity of approximately a tenth of the outburst peak luminosity. This demonstrates that six weeks after the main outburst the source was still active which might indicate that the behavior of the source at the end of the 1996 outburst was similar to what has been seen during the 2000 and 2002 outbursts (see below).

After SAX J1808.4–3658 was found to harbor a millisecond pulsar [58], the X-ray bursts seen with *BeppoSAX* were scrutinized for potential burst oscillations [17]. A marginal detection of a 401 Hz oscillation was made in the third burst suggesting that the burst oscillations observed in the other, non-pulsating, neutron-star LMXBs indeed occur at their neutron-star spin frequencies. This result has been confirmed by the recent detection of burst oscillations during the 2002 outburst of SAX J1808.4–3658 (see below; [5]).

### The April 1998 outburst

On April 9, 1998, SAX J1808.4–3658 was found to be active again [33] and a public TOO observation cam-



**FIGURE 1.** Examples of the power spectra obtained for the five millisecond pulsars showing the pulsar spikes.

paing on the source was started using the *RXTE/PCA*. From those observations, it was discovered that coherent 401 Hz pulsations were present in the persistent X-ray flux of the source ([58]; Fig. 1), making this source the first accreting millisecond X-ray pulsar discovered. An analysis of the coherent timing properties of the source showed that the neutron star is in a  $\sim 2$ -hr binary system with a very low mass companion [4]. The limited amount of *RXTE/PCA* data obtained during this outburst yielded only an upper limit of  $< 7 \times 10^{-13} \text{ Hz s}^{-1}$  on the pulse-frequency derivative [4].

The source flux during the 1998 outburst first showed a steady decline in X-ray flux, which accelerated after  $\sim 2$  weeks ([13, 6]; Fig. 2). This behavior has been attributed to the fact that the source might have entered the ‘propeller regime’ in which the accretion of matter is centrifugally inhibited [13]. However, the fact that after the onset of the steep decline the pulsations could still be detected [6] makes this interpretation doubtful. A week after the onset of this steep decline, the flux leveled off [6, 54], but the X-ray flux behavior of the source at the end of the outburst remains unclear, since no further *RXTE/PCA* observations were made. It is possible that the source might have displayed a similar long-term episode of low-luminosity activity as seen at the end of the 2000 and 2002 outbursts (see below and Fig. 2).

Studies of the X-ray spectrum ([13, 15]; see also [10, 38]) and the aperiodic rapid X-ray variability ([59, 50]; see also Fig. 6) showed an object that, apart from its pulsations, is remarkably similar to LMXBs with comparable luminosities (the atoll sources). There is apparent modulation of the X-ray intensity at the orbital pe-

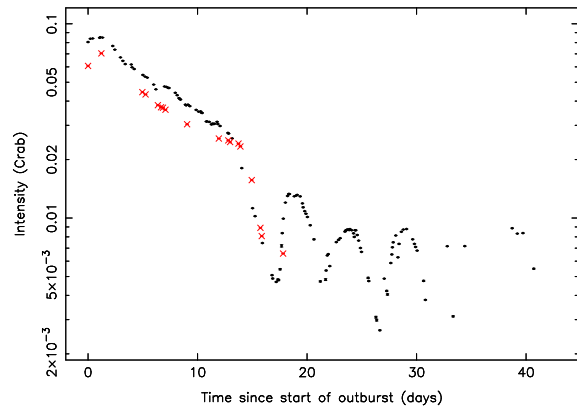
riod, with a broad minimum when the pulsar is behind the companion [4, 15]. Cui et al. [6] and Ford [7] reported on the harmonic content, the energy dependency, and the soft phase lag of the pulsations. The main result of those studies is that the low-energy pulsations lag the high-energy ones by as much as  $\sim 200 \mu\text{s}$  ( $\sim 8\%$  of the pulsation period; see [6, 7, 38] for explanations).

SAX J1808.4–3658 was also detected in the optical, IR, and in radio bands. Its optical/IR counterpart (later named V4580 Sgr; [21]) was discovered by Roche et al. [42] and subsequently confirmed by Giles et al. [11]. A detailed study of the optical behavior during this outburst can be found in Giles et al. [12] and Wang et al. [54]. Giles et al. [12] also reported that the optical flux was modulated at the 2-hr orbital period. A model of the X-ray and optical emission from the system using an X-ray-heated accretion disk model, gave a best fit values of the  $A_V$  of 0.68 and the inclination of  $\cos i = 0.65$  [54], resulting in a mass of the companion of  $0.05\text{--}0.10 M_\odot$ . Some of the IR fluxes were too high to be consistent with emission from the disk or the companion star, even when considering X-ray heating. This IR excess might be due to synchrotron processes, possibly related to an outflow or ejection of matter [54]. Such an event was also suggested by the discovery of the radio counterpart [8]. The source was detected with a 4.8 GHz flux of  $\sim 0.8$  mJy on April 27, 1998, but it was not detected at other epochs.

## The January 2000 outburst

On January 21, 2000, SAX J1808.4–3658 was again detected [62] with the *RXTE/PCA* but this time at a flux level of  $\sim 10\text{--}15$  mCrab (2–10 keV). This is only about a tenth of the fluxes observed during the peak of the previous outbursts. Furthermore, it was found to exhibit low-level activity for months [62]. Due to solar constraints the source could not be observed before January 21 but it is likely that a true outburst occurred before that date and only the end stages of this outburst could be observed. This is supported by the very similar behavior of the source observed near the end of its 2002 outbursts (Fig. 2).

During the 2000 outburst, the source was observed (using *RXTE/PCA*) at luminosities of  $\sim 10^{35} \text{ ergs s}^{-1}$  on some occasions, but on others (a few days earlier or later) the source had luminosities of only  $\sim 10^{32} \text{ ergs s}^{-1}$  (as seen during *BeppoSAX* and *XMM-Newton* observations [63, 56]). This demonstrates that SAX J1808.4–3658 exhibited extreme luminosity variations by a factor of  $> 1000$  on timescales of days. During the episodes of low-level activity in the *RXTE/PCA* observations it was also found that on several occasions SAX J1808.4–3658



**FIGURE 2.** The *RXTE*/PCA light curves of SAX J1808.4–3658 during its 1998 (red crosses) and 2002 outbursts (black dots). The data were taken from van Straaten et al. [50]

exhibited strong (up to 100% rms amplitude) and violent flaring behavior with a frequency of  $\sim 1$  Hz ([48, 55]; Fig. 1 in [57]). During this episode of low-level activity, the pulsations were also detected but the limited amount of observing time and the low source flux did not allow for an independent determination of the orbital parameters and the pulse-frequency derivative.

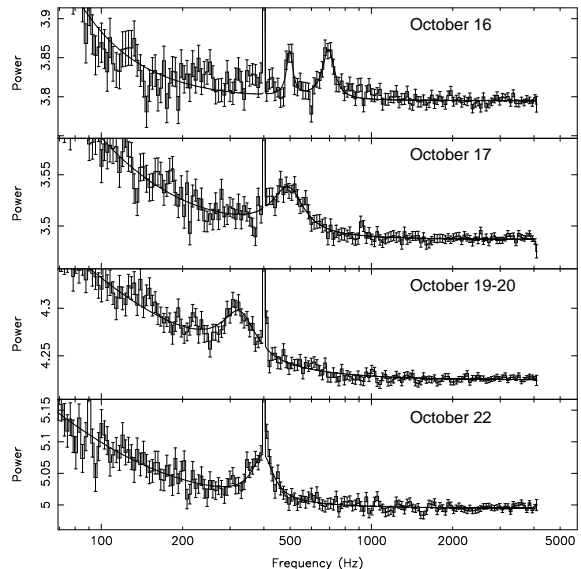
In optical, the source was also detected, albeit at a lower brightness than during the 1998 outburst [52], consistent with the lower observed X-ray fluxes. The source was frequently observed during this outburst and the results were presented by Wachter et al. ([53]; see also the discussion by Wijnands [57]).

## The October 2002 outburst

In October 2002, the fourth outburst of SAX J1808.4–3658 was detected [27], immediately launching an extensive *RXTE*/PCA observing campaign. The main results are summarized below.

### *The X-ray light curve*

The light curve for this outburst is shown in Figures 2 and 5. During the first few weeks, the source decayed steadily, until the rate of decline suddenly increased, similar to what was observed during the 1998 outburst (in Fig. 2 the 1998 outburst light curves is also plotted for comparison). During both the 1998 and 2002 outbursts, the moment of acceleration of the decline happened at about two weeks after the peak of the outburst. Approximately five days later the X-ray fluxes rapidly increased again until it reached a peak of about a tenth of the outburst maximum. After that SAX J1808.4–3658 entered a



**FIGURE 3.** The power spectra obtained for SAX J1808.4–3658 during its 2002 outburst showing the kHz QPOs. [64]

state in which its flux fluctuated rapidly on time scales of days to hours, very similar to the low-level activity seen during its 2000 outburst. The 2002 outburst light curve is the most detailed one seen for SAX J1808.4–3658 and it exhibits all features seen during its previous outbursts (the initial decline, the increase in the decline rate, the long-term activity), demonstrating that this is typical behavior for this source.

### *The kHz QPOs*

Wijnands et al. [64] reported the discovery of two simultaneous kHz QPOs during the peak of the 2002 outburst, with frequencies of  $\sim 700$  and  $\sim 500$  Hz (Fig. 3 top), making this the first detection of twin kHz QPOs in a source with a known spin-frequency. The frequency separation between the two peaks is  $\sim 200$  Hz. This is significantly below the 401 Hz expected in the beat-frequency models proposed to explain the kHz QPOs and, therefore, those models are falsified by the detection of the kHz QPOs in SAX J1808.4–3658. However, the fact that the peak separation is consistent with half the spin frequency suggests that the kHz QPOs are indeed connected to the neutron-star spin frequency, albeit in a way not predicted by any existing model. The lower-frequency kHz QPO was only seen on October 16, 2002 (i.e., during the peak of the outburst) but the higher-frequency kHz QPO could be traced throughout the main part of the outburst ([64]; Fig. 3). Besides the twin kHz QPOs, a third kHz QPO was observed with frequencies ( $\sim 410$  Hz) just exceeding that of the pulse [64]. The

nature of this QPO is currently still unclear (see [64] for a discussion).

Wijnands et al. [64] pointed out that there appear to exist two classes of neutron-star LMXBs: the 'fast' and the 'slow' rotators. The fast rotators have spin frequencies  $\gtrsim 400$  Hz and the peak separation between the kHz QPOs is approximately equal to half the spin frequency. In contrast, the slow rotators have spin frequencies below  $\lesssim 400$  Hz and a peak separation roughly equal to the spin frequency. The kHz QPO results obtained for SAX J1808.4–3658 have already spurred new theoretical investigations into the nature of the kHz QPOs [23, 25].

#### *X-ray bursts and burst oscillations*

During the first five days of the 2002 outburst, four type-I X-ray bursts were observed, all of which exhibited burst oscillations [5]. The frequency in the burst tails was constant and identical to the spin frequency, while the oscillation in the burst rise showed evidence of a rapid frequency drift of up to 5 Hz. No oscillations were seen during the peak of the bursts. This behavior is similar to the burst oscillations seen in other, non-pulsating neutron-star LMXBs, demonstrating that burst-oscillations indeed occur at the neutron-star spin frequency in all sources. The spin frequency is now known for 16 LMXBs with the highest spin frequency being 619 Hz. Chakrabarty et al. [5] used the sample of burst-oscillation sources to demonstrate that neutron stars in LMXBs spin well below their break-up frequency. This could suggest that the neutron stars are limited in their spin frequencies, possibly due to gravitational radiation.

#### *The pulsations*

Pulsations were detected at all flux levels with an amplitude of 3%–10%. The pulsar was spinning down at a constant rate (mean spin-down rate of  $2 \times 10^{-13}$  Hz  $s^{-1}$ ; [5]), despite a large dynamic range in X-ray flux. The magnitude of the pulse-frequency derivative exceeds the maximum value expected from accretion torques by a factor of 5. The timing history also contains a small glitch with a very rapid recovery time scale. There was no evidence for a 200.5 Hz subharmonic in the data (upper limit of 0.38% of the signal at 401 Hz; [64]) confirming the interpretation of 401 Hz as the pulsar spin frequency. A detailed analysis will be presented elsewhere [36].

#### *The low-frequency QPOs*

During the peak of the outburst and subsequent decay, broad-noise and QPOs with frequencies between

10 and 80 Hz were detected in the power spectra ([57]; Fig. 6). Similar phenomena have been observed in other non-pulsating systems and are likely related to the noise components seen in SAX J1808.4–3658. Van Straaten et al. [49, 50] have studied the broad-band power spectra (including the noise components, the low-frequency QPOs, and the kHz QPOs) of SAX J1808.4–3658 in detail as well as the frequency correlations between the different power-spectral components. Interestingly, using those frequency correlations, van Straaten et al. [49] suggested that the higher-frequency kHz QPO could also be identified during the 1998 outburst but at the lowest frequencies found so far in any kHz QPO source (down to  $\sim 150$  Hz). Previous work [59] on the aperiodic timing features of SAX J1808.4–3658 during its 1998 outburst already found these features but they could not be identified as the higher-frequency kHz QPO due to their low frequency and broad character.

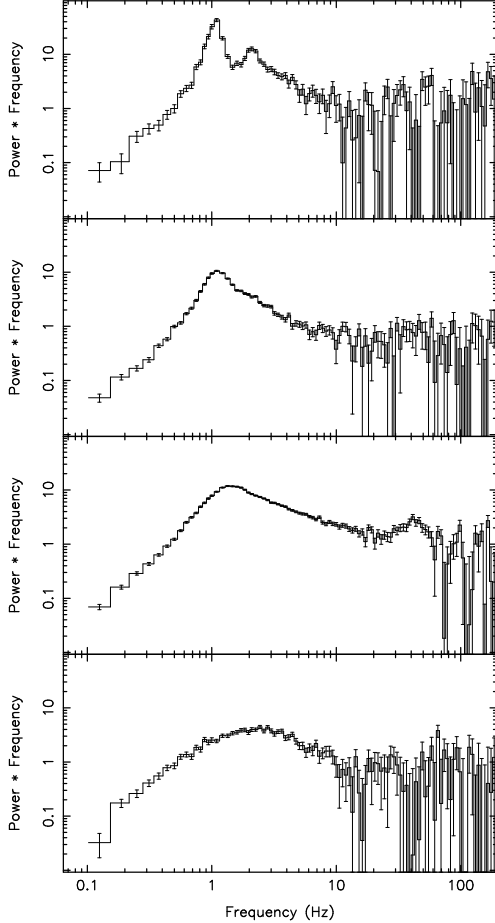
Van Straaten et al. [49, 50] also compared the results for SAX J1808.4–3658 with those obtained for other, non-pulsating neutron-star LMXBs and found that the frequency correlations in SAX J1808.4–3658 are similar to those seen in the other non-pulsating sources, but that they show a shift in the frequency of the kHz QPOs. It is unclear what the physical mechanism(s) is behind this difference between sources [49, 50].

As can be seen from Figure 2, during both the 1998 and 2002 outbursts of SAX J1808.4–3658, the source exhibited similar X-ray fluxes. However, at similar flux levels, the characteristic frequencies observed during the 1998 outburst are much lower (factor 10) than during the 2002 outburst ([50]; see also Fig. 6). Again it is unclear what causes this huge difference between the two outbursts but it might be related to the 'parallel track' phenomena observed for the kHz QPOs (e.g., [47]).

#### *The violent 1 Hz flaring*

Violent flaring was observed on many occasions at a  $\sim 1$  Hz repetition frequency during the late stages of the 2002 outburst (Fig. 4), similar to what had been observed during the 2000 outburst. This proves that also this violent flaring is a recurrent phenomenon and can likely be observed every time the source is in this prolonged low-level activity state. Preliminary results presented in Figure 4 show examples of power spectra obtained during the end stages of the 2002 outburst. During certain observations the 1 Hz QPO is rather narrow and its first overtone can be seen clearly (Fig. 4 top panel). During other observations, the 1 Hz QPO is much broader and its wings blend with the first overtone (Fig. 4 middle two panels). In addition to the 1 Hz QPO, QPOs around 30–40 Hz are sometimes seen (see also [50]). It is unclear if this 30–40 Hz QPO is related to the low-frequency QPOs discussed

## XTE J1751–305



**FIGURE 4.** The 1 Hz flaring (represented via power spectra) as observed during the 2002 outburst of SAX J1808.4-3658.

above or if it is due to a different mechanism. During certain observations the 1 Hz QPO becomes very broad, turning into a band-limited noise component (Fig. 4 bottom panel). A detailed analysis of the 1 Hz flaring phenomenon is in progress.

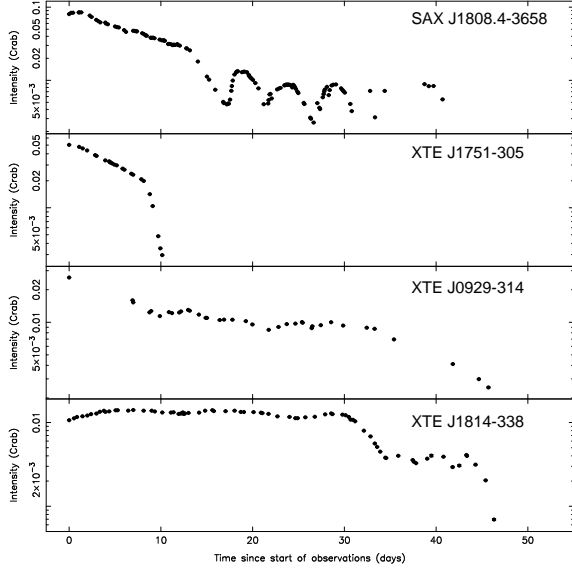
### *Observations at other wavelengths*

Rupen et al. [44] detected the source at radio wavelengths during the 2002 outburst. On October 16–17, 2002, they found a 0.3–0.44-mJy source at 8.5 GHz. Monard [35] reported that on October 16 the optical counterpart was detectable at magnitudes similar to those observed at the peak of the 1998 outburst.

The second accretion-driven millisecond pulsar (XTE J1751–305) was discovered on April 3, 2002 [26]. Its spin frequency is 435 Hz (Fig. 1) and the neutron star is in a very small binary with an orbital period of 42 minutes. The timing analysis of the pulsations gave a minimum mass for the companion of  $0.013 M_{\odot}$  and a pulse-frequency derivative of  $< 3 \times 10^{-13} \text{ Hz s}^{-1}$ . Assuming that the mass transfer was driven by gravitational radiation, the distance toward the source could be constrained to be  $> 7 \text{ kpc}$  with a mass for the companion of  $0.013\text{--}0.035 M_{\odot}$ , which suggests a heated helium dwarf [26]. *Chandra* also observed the source, resulting in an arc-second position [26].

The source reached a peak luminosity of  $> 2 \times 10^{37} \text{ ergs s}^{-1}$ , an order of magnitude brighter than the peak luminosity of SAX J1808.4–3658. However, the outburst was very short with an e-folding time of only  $\sim 7$  days (compared to  $\sim 14$  days for SAX J1808.4–3658; Fig. 5) resulting in a low outburst fluence of only  $\sim 2.5 \times 10^{-3} \text{ ergs cm}^{-2}$  [26]. A potential re-flare was seen two weeks after the end of the outburst during which also a type-I X-ray burst was seen. Analysis of the burst indicated that the burst did not come from XTE J1751–305 but it likely originated from the bright X-ray transient in Terzan 6 [18]. It was also determined that the transient in Terzan 6 could not have produced the re-flare [18] suggesting that this re-flare could still have come from XTE J1751–305. However, van Straaten et al. [50] suggested (based on a X-ray color study using *RXTE*/PCA) that this re-flare is caused by one of the background sources and not by XTE J1751–305. Van Straaten et al. [50] also investigated the aperiodic timing properties of the source (an example power spectrum is shown in Fig. 6) and the correlations between the characteristic frequencies of the observed power-spectral components. The frequency correlations were similar to those of the non-pulsating neutron-star LMXBs. In contrast with the results obtained for SAX J1808.4–3658 (see above), no frequency shift was required for XTE J1751–305 to make the frequency correlations consistent with those of the non-pulsating sources. Using these correlations, van Straaten et al. [50] suggested that the highest-frequency noise components in XTE J1751–305 are likely due to the same mechanisms as the kHz QPOs. They also investigated the correlations between the characteristic frequencies and the X-ray colors of the source and concluded that it did not behave like an atoll source.

A previous outburst in June 1998 was detected using archival *RXTE*/ASM data [26], suggesting a tentative recurrence time of  $\sim 3.8$  years. Miller et al. [34] reported on high spectral resolution data of the source obtained with *XMM-Newton*. They only detected a continuum spectrum dominated by a hard power-law shaped component

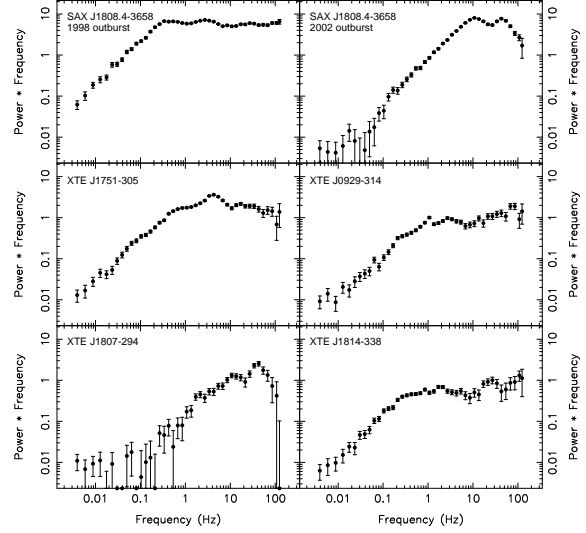


**FIGURE 5.** The *RXTE*/PCA light curve of SAX J1808.4–3658, XTE J1751–305, XTE J0929–314, and XTE J1814–338. The data for SAX J1808.4–3658 was obtained during its 2002 outburst. The data were taken from van Straaten et al. [50]

(power-law index of  $\sim 1.44$ ) with a 17 % contribution to the 0.5–10 keV flux by a soft thermal (black-body) component with temperature of  $\sim 1$  keV. Searches for the optical and near-infrared counterparts were performed but no counterparts were found [19], likely due to the high reddening toward the source. These non-detections did not constrain any models for the accretion disk or possible donor stars.

### XTE J0929–314

The third accretion-driven millisecond X-ray pulsar XTE J0929–314 was already detected with the *RXTE*/ASM on April 13, 2002 [39], but not until May 2 (when observations of the source were made using the *RXTE*/PCA) was it found to be harboring a millisecond pulsar with a pulsation frequency of 185 Hz ([40]; Fig. 1). Galloway et al. [9] reported on the detection of the 44-min orbital period of the system. A minimum mass of  $0.008 M_{\odot}$  was obtained for the companion star and a pulse-frequency derivative of  $(-9.2 \pm 0.4) \times 10^{-14} \text{ Hz s}^{-1}$ . Galloway et al. [9] suggested that this spin down torque may arise from magnetic coupling to the accretion disk, a magneto-hydrodynamic wind, or gravitational radiation from the rapidly spinning neutron star. Assuming gravitational radiation as the driving force behind the mass transfer, Galloway et al. [9] found a lower limit to the distance of 6 kpc. They also reported on the detection of a QPO at 1 Hz (Fig. 6). Full details of this QPO and



**FIGURE 6.** Examples of the aperiodic timing features seen in the five millisecond pulsars (only for frequencies below  $\sim 200$  Hz). For SAX J1808.4–3658 an example is shown for its 1998 and 2002 outbursts.

the other aperiodic power-spectral components are presented by van Straaten et al. [50]. Just as they found for SAX J1808.4–3658, the frequency correlations for XTE J0929–314 were similar to those observed for the non-pulsating sources but with an offset in the frequencies of the highest-frequency components. These correlations allowed van Straaten et al. [50] to identify those components as related to the kHz QPOs. Studying the correlated spectral and timing variability, they concluded that the behavior of XTE J0929–314 was consistent with that of an atoll source.

Juett et al. [20] obtained high resolution spectral data using the *Chandra* gratings. Again the spectrum is well fitted by a power-law plus a black body component, with a power-law index of 1.55 and a temperature of 0.65 keV. Similar to XTE J1751–305, no emission or absorption features were found. No orbital modulation of the X-ray flux was found implying an upper limit on the inclination of  $85^{\circ}$ . Greenhill et al. [14] reported the discovery of the optical counterpart of the system. Castro-Tirado et al. [3] obtained optical spectra of the source on May 6–8 in the range 350–800 nm and found emission lines from the C III - N III blend and H-alpha, which were superposed on a blue continuum. These optical properties are typical of X-ray transients during outburst. Rupen et al. [43] discovered the radio counterpart of the source using the VLA with a 4.86 GHz flux of 0.3–0.4 mJy.

## XTE J1807–294

The fourth millisecond X-ray pulsar XTE J1807–294 with a frequency of 191 Hz, was discovered on February 21, 2003 ([28]; Fig. 1). The peak flux was only 58 mCrab (2–10 keV). The orbital period was determined [30] to be  $\sim 40$  minutes making it the shortest period of all accretion-driven millisecond pulsars known. Using a *Chandra* observation, Markwardt et al. [30] reported the best known position of the source. In the *RXTE*/PCA data, kHz QPOs have been detected for this system and the results obtained from a full analysis of those data will be reported elsewhere [32]. An example of the power-spectral components at frequencies below 200 Hz is shown in Figure 6. Campana et al. [2] reported on a *XMM-Newton* observation of this source taken on March 22, 2003. Assuming a distance of 8 kpc, the 0.5–10 keV luminosity during that observation was  $2 \times 10^{36}$  ergs s $^{-1}$ . They could detect the pulsations during this observation with a pulsed fraction of 5.8% in the 0.3–10 keV band (increasing with energy) and a nearly sinusoidal pulse profile (see also [22]). The spectral data are well fit by a continuum model, assumed to be an absorbed Comptonisation model plus a soft component. The latter component only contributed 13% to the flux. Again no emission or absorption lines were found. No detections of the counterparts of the system at other wavelengths have been reported so far.

## XTE J1814–338

The fifth system (XTE J1814–338) was discovered on June 5, 2003 and has a pulse frequency of 314 Hz ([29]; Fig. 1), with an orbital period of 4.3 hr and a minimum companion mass of  $0.15 M_{\odot}$  [31]. This 4.3 hr orbital period makes it the widest binary system among the accretion-driven millisecond pulsars and also the one most similar to the general population of the low-luminosity neutron-star LMXBs (the atoll sources). Many type-I X-ray bursts with burst oscillations were found with a frequency consistent with the neutron star spin frequency [31, 46]. A distance of  $\sim 8$  kpc was obtained from a burst which likely reached the Eddington luminosity. The burst oscillations are strongly frequency and phase locked to the persistent pulsations (as was also seen for SAX J1808.4–3658; [5]) and two bursts exhibited evidence for a frequency decrease of a few tenths of a Hz during the onset of the burst, suggesting a spin down. Strohmayer et al. [46] also reported on the detection of the first harmonic of the burst oscillations: the first time that this has been found for any burst-oscillation source. This harmonic could arise from two hot-spots on the surface, but they suggested that if the burst oscillations arise

from a single bright region, the strength of the harmonic would suggest that the burst emission is beamed (possibly due to a stronger magnetic field strength than in non-pulsating LMXBs).

Wijnands & Homan [60] analyzed the *RXTE*/PCA data of the source obtained between June 8 and 11, 2003. The overall shape of the 3–60 keV power spectrum is dominated by a strong broad band-limited noise component (Fig. 6), which could be fitted by a broken power-law model with a broad bump superimposed on it at frequencies above the break frequency. Van Straaten et al. [50] performed an in-depth analysis of all publicly available *RXTE*/PCA data of the source to study the power-spectral components and the correlations between their characteristic frequencies. Using those correlations and by comparing them to other sources, they could identify several components as related to the kHz QPOs. They also found that the frequency correlations were identical to the non-pulsating sources with no need for a frequency shift. This is similar to what they found for XTE J1751–305 but different from SAX J1808.4–3658 and XTE J0929–314. The reason(s) for this difference between accreting millisecond pulsars is not known (see [50] for a discussion). From the correlations between the spectral and timing variability it was also concluded that the behavior of XTE J1814–338 was consistent with that of an atoll source ([50]; see also [60]).

Wijnands & Reynolds [61] reported that the position of XTE J1814–338 was consistent with the *EXOSAT* slew source EXMS B1810–337 which was detected on September 2, 1984. If XTE J1814–338 can indeed be identified with EXMS B1810–337, then its recurrence time can be inferred to be less than 19 years but more than 5 years (the time since the *RXTE*/PCA bulge scan observations started in February 1999), unless the recurrence time of the source varies significantly. Krauss et al. [24] reported the best position of the source as obtained using *Chandra* and on the detection of the likely optical counterpart (with magnitudes of  $B = 17.3$  and  $R = 18.8$  on June 6). Steeghs [45] performed optical spectroscopy of this possible counterpart and reported prominent hydrogen and helium emission lines, confirming the connection between the optical source and XTE J1814–338.

## CONCLUDING REMARKS

From the current review it is clear that *RXTE* is vital to the discovery and study of accretion-driven millisecond X-ray pulsars. Thanks to *RXTE* we know about the existence of five such systems. The detailed studies performed with *RXTE* for those systems have yielded breakthroughs in our understanding of kHz QPOs and burst oscillations. Furthermore, three of these accreting pulsars

are in ultrashort binaries which will constrain evolutionary paths for this type of system (e.g., see [37]). However, it is also clear that the five systems do not form a homogeneous group; their pulsation frequencies span the range between 185 Hz and 435 Hz (Fig. 1), their orbital periods between 40 minutes and 4.3 hrs, and their X-ray light curves are very different (Fig. 5). More well studied outbursts of the currently known systems are needed as well as discoveries of additional systems. At the moment, only *RXTE* is capable of performing the necessary timing observations. After *RXTE* the need for an instrument with at least similar or better capabilities is highly desirable for our understanding of accretion-driven millisecond pulsars and their connection with the non-pulsating neutron-star LMXBs.

For lack of space this review has focused on observational findings on accretion-driven millisecond pulsars during outbursts. For information on their quiescent states and on theoretical progress, I refer to [57].

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